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AGARD REPORT No.751

**Automated Measurement of Crack
Length and Load Line Displacement
at Elevated Temperature**

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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.751

AUTOMATED MEASUREMENT OF CRACK LENGTH AND LOAD LINE
DISPLACEMENT AT ELEVATED TEMPERATURE

by

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ABSTRACT

AUTOMATED MEASUREMENT OF CRACK LENGTH AND LOAD LINE DISPLACEMENT AT ELEVATED TEMPERATURE

Test results reported in the literature show that, in creep cracking tests at elevated temperature under steady load, the crack growth rate correlates best with the contour integral C^* , also called J^* , in comparison to other possible parameters. In the case of fatigue at elevated temperature, the crack growth rate correlates best with C^* if cracking is predominantly time dependent. If, however, cracking is predominantly cycle dependent the crack growth rate correlates best with the range ΔJ of the contour integral J . It is discussed that in such testing C^* and J are fairly easily determined if, apart from load and crack length, the load line displacement is measured.

A description is given of a test set-up developed for elevated temperature creep cracking test in which crack length was measured with the electrical potential drop method and load line displacement was measured with two inductive transducers located inside the furnace. Measurement was automated with the aid of a personal computer which controlled the measurements and processed the results automatically. This set-up can be adapted for elevated temperature fatigue testing.

* * * *

RESUME

CONTROLE AUTOMATISE DE LA LONGUEUR DES CRIQUES DE FLUAGE ET DEPLACEMENT DE LA LIGNE DE CHARGE A DES TEMPERATURES ELEVEES

Les résultats d'essais indiqués dans la littérature démontrent qu'en ce qui concerne les contrôles des criques de fluage effectués à des températures élevées et à charge constante, c'est l'intégrale de contour C^* , appelée aussi J^* , qui correspond à la meilleure représentation de la vitesse de propagation des criques par rapport aux autres paramètres possibles. Dans le cas des criques de fatigue constatées à des températures élevées, C^* correspond à la meilleure représentation de la vitesse de propagation des criques, à condition que la fissuration soit principalement fonction du temps. Par contre, si la fissuration est principalement fonction du cycle, la vitesse de propagation des criques se trouve le mieux représentée par la variation ΔJ de l'intégrale de contour J . Les valeurs de C^* et de J sont relativement faciles à déterminer lors des essais si le déplacement de la ligne de charge est mesuré en même temps que la charge et la vitesse de propagation des criques.

La communication comporte une description du montage ayant servi aux essais des criques de fluage à des températures élevées, où la longueur des criques a été mesurée selon la méthode de chute de potentiel et le déplacement de la ligne de charge à l'aide de deux transducteurs inductifs, montés à l'intérieur du four. Les contrôles ont été automatisés à l'aide d'un ordinateur personnel lequel a permis la commande des mesures et le traitement automatique des résultats. Ce montage peut être adapté pour l'exécution d'essais de fatigue à des températures élevées.

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SUMMARY

Test results reported in the literature show that in creep cracking tests at elevated temperature under steady load, the crack growth rate correlates best with the contour integral C^* , also called J^* , in comparison to other possible parameters. In the case of fatigue at elevated temperature, the crack growth rate correlates best with C^* if cracking is predominantly time dependent. If, however, cracking is predominantly cycle dependent the crack growth rate correlates best with the range ΔJ of the contour integral J . It is discussed that in such testing C^* and J are fairly easily determined if, apart from load and crack length, the load line displacement is measured. A description is given of a test set-up developed for elevated temperature creep cracking tests in which crack length was measured with the electrical potential drop method and load line displacement was measured with two inductive transducers located inside the furnace. Measurement was automated with the aid of a Personal Computer which controlled the measurements and processed the results automatically. This set-up can be adapted for elevated temperature fatigue testing.

This paper was prepared for presentation at a meeting of an Ad Hoc Group on High Temperature Cyclic Behaviour of Aerospace Materials at the occasion of the 65th meeting of the AGARD Structures and Materials Panel in Cesme, Turkey, October 1987.

1. INTRODUCTION

During the afternoon of Wednesday 29th April 1987 in Madrid, at the occasion of the 64th meeting of AGARD Structures and Materials Panel, a meeting was held of an Ad Hoc Group on High Temperature Cyclic Behaviour of Aerospace Materials. A draft programme prepared by Messrs Gostelow (RAE) and Jeal (RR) was discussed. The programme involves Crack Growth Testing and Low Cycle Fatigue Testing at elevated temperatures. It was concluded that the proposed activity is very difficult experimentally and that it lacks proper theoretical modelling, which makes the selection of test specimens very difficult. It was decided that the group should meet once more as an Ad Hoc Group to hear pilot papers on theoretical modelling, reviews of experimental methods, instrumentation and materials of interest.

One of the present authors stressed the importance of extensometry also in the case of Crack Growth Testing because it was essential to measure the Load Line Displacement or COD if one were to evaluate the usefulness of parameters other than the stress intensity factor K , such as the time independent elasto-plastic contour integral J and the time dependent contour integral C^* , also indicated as J^* .

There is ample evidence that for creep ductile materials C^* , as a parameter to correlate with the creep crack growth rate da/dt , is superior to parameters such as K , J , net section stress or reference stress, see e.g. references 1 and 2.

Sadananda and Shahinian (Ref. 3) have shown that, in the case of high temperature fatigue crack growth in Udimet 700, AISI 316 and Inconel 718, J is better behaved as a correlating parameter for crack growth rate than K . Ohji and Kubo et al. (Refs. 4, 5, 6) have shown that for austenitic stainless steel of the 316 type, fatigue at elevated temperature is time dependent at low frequency and cycle dependent at high frequency. The growth rate correlates best with J^* in the former case and with ΔJ in the latter case.

For the test reported in reference 2 automated equipment was developed to measure crack growth using the electrical potential drop method and to measure load line displacement with inductive transducers inside the furnace. This equipment will be described in the present paper, but first it will be discussed how J and J^* can be determined if the load line displacement v is known.

2. DETERMINATION OF J AND J^* OR C^*

As was discussed by one of the present authors in reference 1 and in particular by Sadananda and Shahinian in reference 7, the contour integrals J and J^* can be related to the strain energy U and the strain energy rate $\dot{U} = dU/dt$, whereas these quantities can be determined from tests on cracked bodies by measuring load P , crack length a and load line displacement v .

The operating definitions of J and J^* are:

$$J = - \frac{1}{B} \left. \frac{dU}{da} \right|_v$$

$$J^* = - \frac{1}{B} \left. \frac{d\dot{U}}{da} \right|_v$$

where B is the specimen thickness.

Various schemes have been developed to determine J and J^* empirically by processing diagrams involving the quantities, P , a , \dot{a} , v and \dot{v} . This way of determination is quite cumbersome and normally requires the testing of more than one specimen.

A quicker way is offered, however, by an analysis in which strain ϵ and strain rate $\dot{\epsilon}$ are assumed to be power functions of stress σ .

Such analyses have been made by Hutchinson, Goldman, Shih and Kumar et al. If it is assumed that:

$$\frac{\epsilon}{\epsilon_0} = \alpha \left(\frac{\sigma}{\sigma_0} \right)^m$$

there is found that

$$J = g_1 \left(\frac{a}{w}, m \right) \left\{ \alpha \sigma_0 \epsilon_0 (w-a) \left(\frac{P}{P_0} \right)^{m+1} \right\}$$

$$v = g_3 \left(\frac{a}{w}, m \right) \left\{ \alpha \epsilon_0 a \left(\frac{P}{P_0} \right)^m \right\}$$

Likewise for

$$\frac{\dot{\epsilon}}{\dot{\epsilon}_0} = \beta \left(\frac{\sigma}{\sigma_0} \right)^n$$

$$J^* = h_1 \left(\frac{a}{w}, n \right) \left\{ \beta \sigma_0 \dot{\epsilon}_0 (w-a) \left(\frac{P}{P_0} \right)^{n+1} \right\}$$

$$\dot{v} = h_3 \left(\frac{a}{w}, n \right) \left\{ \beta \dot{\epsilon}_0 a \left(\frac{P}{P_0} \right)^n \right\}$$

The authors named above have made systematic calculations of the quantities g_1 and g_3 and h_1 and h_3 for a variety of standard specimens and in particular the Compact Tension Specimen and have tabulated their results as functions of a/w and m or n in a series of publications and especially in references 8 and 9. Note that w is the specimen width measured from the load line to the back face of the CT specimen.

It can be remarked that for equal values of a/w and for $m=n$, there is found that $g_1 = h_1$ and $g_3 = h_3$ on account of the so-called plastic analogue.

In the above equations:

$$P_0 = 1.455 \eta (w-a) \sigma_0 B_n \quad (\text{plane strain})$$

$$\text{with } \eta = \left\{ \left(\frac{2a}{b} \right)^2 + 2 \left(\frac{2a}{b} \right) + 2 \right\}^{\frac{1}{2}} - \left\{ \frac{2a}{b} + 1 \right\}$$

Here B_n is net specimen thickness and $b = (w-a)$.

The equations for J and v and for J^* and \dot{v} can be combined to yield:

$$J = k \frac{P}{B_n (w-a)} \cdot v$$

$$J^* = C^* = k^* \frac{P}{B_n (w-a)} \cdot \dot{v}$$

$$\text{with } k = \frac{g_1}{g_3} \left(\frac{w}{a} - 1 \right) \frac{1}{1.455 \eta}$$

$$\text{and } k^* = \frac{h_1}{h_3} \left(\frac{w}{a} - 1 \right) \frac{1}{1.455 \eta}$$

Note that k and k^* are functions of a/w and m , respectively n , and can be calculated from the tables referred to before.

For plane stress similar equations apply, with 1.455 replaced by 1.072.

It is readily seen that with the above equations and with the tabulated values of the parameters involved J and J^* are easily calculated from test results comprising load P , crack length a , load line displacement v and the time derivative of the latter.

3. BASIC TEST SET-UP

The specimen selected for the test reported in reference 2 was of the Compact Tension type. It had an overall width in the crack growth direction of 45 mm and a height of 43.2 mm. Two thicknesses were used, viz. 12 and 10.8 mm. Side grooves were applied in such a manner that the ratio of net to gross thickness B/B_0 equalled 0.75 in both cases. These dimensions were dictated by the geometry of the tubular material available for testing and were a compromise aiming at reasonable overall size and thickness. The specimens were precracked at room temperature in an AMSLER Vibrophore fatigue machine. The specimens were loaded in an AMSLER type ST F M 346 creep frame with a capacity of 30 kN.

Heating was accomplished with a split-type AMSLER furnace originally developed for use in an AMSLER Vibrophore fatigue machine. Temperature was controlled with an AMSLER TR 596 controller in which a bimetallic element controls the fractional duration of current application as the fractional duration of electrical contact between an electrode and a rotating slant disc.

Figures 1 and 2 give an impression of the set-up.

Specimen temperature was measured with a thermocouple inserted in a hole drilled in the specimen backface near the top edge.

Load line displacement was measured with two SCHAEVITZ type 250 XS-ZT inductive transducers or LVDT's attached to the upper and lower faces of the specimen, in such a way that the plane through their axes contained the load line.

Crack length was measured using the DC potential drop method. This involved a DELTA type S.5-30 stabilized DC source, a KEITHLEY No. 181 digital nanovoltmeter and a KEITHLEY Series 500 Data Acquisition System (DAS).

The whole system was controlled by an IBM Personal Computer provided with an IEEE interface card, as can be seen in figure 3.

Permanent records of the measured data were made with an IBM 80 CPS graphics printer and a YEW Type 3056 vertical penrecorder.

4. CRACK LENGTH MEASUREMENT

The stainless steel current supply leads were attached to the notched front face of the specimen close to the upper and lower edges with the aid of set screws. The stainless steel potential leads were inserted in holes drilled in the front face, but close to the notch edges. The leads were secured by peening.

The positions of the supply and the measurement leads were selected on the basis of an analysis made by Aronson and Ritchie (Ref. 10). Of some possible locations the selected ones provided a maximum absolute output voltage and the least sensitivity to small positional variations of the potential leads. The supply current was stabilized at 10.00 Ampere DC. Note that the specimen was isolated electrically from the creep machine by inserting thin foils of mica in the gaps between the loading pins and the specimen and between the specimen flanks and the loading fork.

To avoid errors due to dissimilar metals contact potentials, the potential drop of about 2 mV was measured with the supply current on and with the supply current off, and the latter was subtracted from the former. In practice this was achieved by zero-setting the KEITHLEY nanovoltmeter in the case the current was off. The current source was switched on and off by the IBM Personal Computer, which was realized through the KEITHLEY DAS which was sending a TTL signal to the current source.

To avoid errors due to temperature variations affecting the metal's resistivity, use was not made of a reference voltage drawn from a companion specimen or from a location on the specimen itself not affected by changes in crack length. Instead the output voltage was corrected directly with the aid of the signal from the thermocouple measuring specimen temperature.

The specimen was calibrated at the measurement temperature of 525 °C by repeatedly extending a crack in room temperature fatigue. The calibration curve has been updated a number of times by incorporating results from specimens tested in creep cracking, which provided information on the initial and the final crack lengths together with the corresponding potential drop values.

It had been measured that a variation of 1 °C around the test temperature of 525 °C resulted in a variation of the potential drop of 0.15/ %. This information was applied in the automatic correction for temperature variations, which remained within ± 2 °C.

After every test the specimen was broken forcefully and the actual values of the initial and final crack lengths were measured from the fracture surfaces. If there were discrepancies between the apparent and the actual crack lengths, the apparent crack lengths were corrected accordingly, if necessary by interpolating linearly between the corrections for the initial and for the final crack lengths.

5. DISPLACEMENT MEASUREMENT

To measure the opening displacements in a plane through the load line, use was made of two SCHAEVITZ type 250XS-ZT LVDT's. Transducers of this type are constructed entirely from inorganic materials. The coils consist of ceramic-insulated silver magnet wire wound on stable fired ceramic coil forms. Joints between magnet wire and lead wires are silver brazed. Ceramic cements and fillers are used to eliminate voids and to distribute the heat evenly throughout the units in order to minimize thermal gradients. Through baking at a high temperature the entire assembly is fused together forming a solidified structure. The coil assembly is fully encased in a welded stainless steel shell, which completely seals out the environment from the windings, while allowing free motion of the rod-shaped magnetic core.

The particular type used has a nominal linear range of ± 6.5 mm (.25 inch). The linearity was ± 0.5 % of the full range. The sensitivity was 12 mV output per Volt input per mm displacement. It could be operated at temperatures between - 195 °C and + 600 °C.

For supply of the primary excitation current, and in order to obtain a DC output signal directly proportional to the core displacement, use was made of two SCHAEVITZ CAS-025 LVDT Signal Conditioners. These are self-contained line-powered units containing a carrier amplifier and a synchronous demodulator circuit.

The particular type used provided an excitation current at a frequency of 2.5 kHz. The units could provide a DC output signal ranging from 0 to ± 10 V.

6. AUTOMATION

The IBM Personal Computer was used to automatically translate the electrical transducer signals into temperatures and lengths but also for overall control of the measurements. In order to perform the first function appropriate calibration files were fed to the PC. In performing the second function the PC acted partly through the KEITHLEY Data Acquisition System.

The KEITHLEY DAS is a central measurement and control system. It contains 4 modules, viz. an Analog Measurement Module, an Analog Output Module, a Digital Input Module and a Digital Output Module. The third one was not used in the present set up.

The AMM is a A-D converter with 12-bits resolution and a non-linearity of $\pm 0.025\%$ of full scale. It can provide amplification ratios of 1, 2, 5 and 10 X with corresponding potential ranges of 10, 5, 2 and 1 Volt.

The AOM is a D-A converter with 12-bits resolution and a non-linearity of $\pm 0.012\%$ of full scale. It can provide amplification ratios of 1, 2, 5 and 10 X with corresponding potential ranges of 10, 5, 2 and 1 Volt.

The DOM has 16 output channels. The maximum output is 28 V and 40 mA. In the present set up the input consisted of analog input signals and the output consisted of analog as well as digital signals. The analog input signals were the amplified signals from the two LVDT's and the amplified thermocouple output. In addition the thermocouple signal was fed directly to the recorder without amplification.

The analog output signals were those for recorder registration of crack length and average displacement.

The digital output consisted of the TTL control signals for current source and recorder. In the system would have to control load application as in a fatigue test use could be made of channels for a "busy" signal and an "external-trigger" signal.

The signal to the recorder was a pulse train (TTC) which activated paper transport. The length of the pulse train determined the length of the paper transport.

For crack length measurement the KEITHLEY Nanovoltmeter was zero'ed. Then the current source was switched on. After a delay of 2 seconds for damping out of disturbances the potential drop was measured. The current source was switched off and the displacements left and right and the amplified temperature signal were input through the DAS.

The temperature in $^{\circ}\text{C}$ did not correspond linearly with the thermocouple voltage. The important range had been divided in two intervals, 500 - 525 and 525 - 550 $^{\circ}\text{C}$ in which there was interpolated linearly. This means that at the correct test temperature of 525 $^{\circ}\text{C}$ no interpolation error was made.

As discussed before, the potential drop was corrected automatically for temperature variation (0.157 % per degree C deviation). Because of a certain instability of the DAS, the last 5 measurements were averaged. Also the crack length was calculated through linear interpolation. The calibration curve had been divided in intervals of 1 mm crack length with the corresponding potentials.

The measured displacements left and right were averaged. The information on the screen consisted of lines giving:

- time of measurement
- crack length (corrected for temperature fluctuations)
- potential drop (corrected for temperature fluctuations)
- displacement left side
- displacement right side
- mean displacement

The time interval between measurements could be selected as necessary and could be changed during the test. The time intervals at which the results were printed could be set independently from the above. Additional registrations could be made if the crack length increments exceeded a preselected value. In addition "manual" measurements and registrations could be made by pressing the proper key (M) on the IBM PC keyboard. On the recorder curves were drawn giving temperature, corrected crack length and mean displacement.

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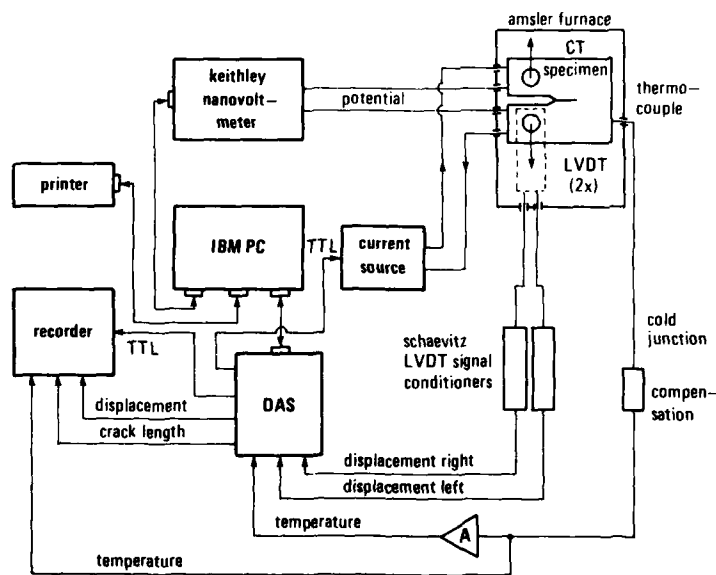
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Fig. 1 Details of the test set-up



Fig. 2 Overview of the test set-up



DAS = KEITHLEY DATA ACQUISITION SYSTEM

TTL = TRANSISTOR-TRANSISTOR-LOGIC (ON-OFF CONTROL SIGNAL)

A = ASTRODATA DC AMPLIFIER

Fig. 3 Measurement circuitry

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